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UNPUBLISHED PRELIMINARY DATA

Observations of the Equatorial Ionosphere using Incoherent Backscatter*

by

Donald T. Farley, Jr.
Jicamarca Radar Observatory, Apartado 3747, Lima, Peru[1]

Quarterly Status Report for 1-1-65 thru 3-31-65

*This paper was presented at the NATO Advanced Study Institute on Electron Density Profiles in the Ionosphere and Exosphere--Finse, Norway, April 1965. It may be referred to as being "in press".

[1]A cooperative project of the Central Radio Propagation Laboratory, National Bureau of Standards, in Boulder, Colorado, and the Instituto Geofisico del Perú, Lima, Perú.

Observations of the Equatorial Ionosphere using Incoherent Backscatter

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ABSTRACT

Measurements of electron density, electron and ion temperature, and ionic composition have been made in Peru using the incoherent backscatter technique. The paper reports some of the more recent results, particularly those of 1-3 February, 1965. In the latter period, continuous measurements of electron density were obtained up to altitudes above 4000 km. Between 3000 and 5000 km, the densities varied by about a factor of two throughout the day. At lower heights there was, at times, strong evidence of rapid vertical motion. During the day, temperature equilibrium between the ions and electrons prevailed above about 400 km, but T_e/T_i reached values approaching three at lower heights. Equilibrium appeared to exist at all heights at night. A limited number of measurements of the ionic composition show no evidence of He^+ ions during the day, and the O^+ and H^+ densities become equal at about 900 km. During the night, however, He^+ does appear to be present in significant amounts, and the relative concentration of O^+ drops to 50% at about 700 km.

[1]A cooperative project of the Central Radio Propagation Laboratory, National Bureau of Standards, in Boulder, Colorado, and the Instituto Geofisico del Perú, Lima, Perú.

1. Introduction

The technique of using incoherent scattering of radio waves by free electrons to study the upper ionosphere is now quite well known. Most of the details of the historical development of this technique were given by Evans[1] at this conference two years ago, and so we shall not repeat them here. Incoherent scattering is a particularly useful tool for studying the topside of the ionosphere, a region inaccessible to the conventional ionosonde. Satellite-borne topside sounders provide wide geographic coverage of the region from h_{max} to about 1000 km, but very limited time coverage; in contrast, incoherent scattering measurements can provide complete time coverage (in some cases to altitudes far beyond 1000 km) at one location. Thus the two techniques nicely complement each other.

The Jicamarca Radar Observatory is located near Lima, Peru at 2° north geomagnetic latitude. The radar transmitter has a peak power of 5×10^{6} watts at a frequency of 49.92 Mc/s; the antenna consists of an array of 9,216 pairs of crossed half-wave dipoles having an area of $8.4 \times 10^{4} m^{2}$. The large antenna and powerful transmitter allow measurements from altitudes of about 150 km up to altitudes beyond one earth radius.

The theory of incoherent scattering has been investigated by a number of authors[2-13] and is now quite well understood. In this paper, we shall only mention those aspects of the theory which are closely related to results obtained at Jicamarca. In the following sections of this paper, we shall describe briefly the various measurement techniques used at Jicamarca and then go on to discuss the results obtained to date.

2. Description of Measurements

The signal returned from the ionosphere by incoherent scattering is affected by the ionosphere in three distinct ways. Thus three different types of measurement can be made, each of which gives independent information about the characteristics of the ionosphere. In simplest terms, the three characteristics of the received signal which can be observed are the power, polarization, and frequency spectrum. The power is a function of the electron to ion temperature ratio T_e/T_i; the rate of rotation of the plane of polarization of a linearly polarized wave (the Faraday rotation) is a function of the electron density; and the spectrum is a function of T_e, T_i, and the ionic composition. Thus, from simultaneous observations of all the characteristics of the signal, one can, in principle, determine the altitude dependence of the electron density, the electron and ion temperatures, and the ionic composition of the ionosphere.

In practice, we do not measure either the plane of polarization or the frequency spectrum directly; it turns out to be more convenient to observe equivalent characteristics of the signal. The Faraday rotation of a linearly polarized wave is of course the result of the slightly different refractive indices corresponding to the two magneto-ionic modes (which, at our frequency of 50 Mc/s, are essentially circularly polarized in spite of the fact that our beam is directed almost perpendicular to the magnetic field). As a result of the slightly different velocities of propagation, the wave in one mode becomes shifted in phase with relation to the other as it passes through the ionosphere. It is this phase shift which we measure. Rather than measure the power spectrum of the signal, we measure the complex time autocorrelation function, which is simply the Fourier transform of the power spectrum and contains exactly the same information.

A. Power Profile. This is conceptually the simplest of the three measurements and is the one most used by other workers. The transmitter is switched alternately between right and left hand circular polarization, and both polarizations are received, using linear envelope detectors. The receiver channels are switched so that one channel contains $(P_s + P_n)^{\frac{1}{2}}$ while the other contains $(P_n)^{\frac{1}{2}}$, P_n and P_s being the mean noise and signal power, respectively. Generally, twenty thousand or more samples are average for each of many heights in a digital integrator and the data is then reduced in a computer, making use of the relation

$$P_s(h) \sim \frac{N}{h^2} f(T_e/T_i) \qquad (1)$$

where h is the altitude ($h = ct/2$ with t being the time between the transmission and reception of the pulse), and N is the electron density. T_e and T_i are the electron and ion temperatures. The function $f(T_e/T_i)$ has been calculated numerically. In many cases f is approximately equal to $(1 + T_e/T_i)^{-1}$. However, the validity of this approximation depends, among other things, on the orientation of the magnetic field with respect to the direction of the radio beam, and it turns out that it cannot be used at Jicamarca.[14] In the data reduction process, the quantity $Nf(T_e/T_i)$, multiplied by an arbitrary normalizing constant, is automatically plotted.

The values of N/h^2 cover a range of about 5 orders of magnitude in the region extending up to 10,000 km. Consequently, to obtain a complete profile of electron density up to such heights, it is necessary to fit together two or three profiles taken with different pulse lengths. Fortunately, at the high altitudes where long pulses (5 ms is the longest pulse used so far) are necessary because of the very weak echo, the ionosphere changes very slowly, with a scale height which is much greater than the pulse length.

The problem of detection is a critical one for the power measurements. Troubles with gain modulation by the varying input signal have been experienced with the best available square law detectors, and attempts to improve this feature have proven to be only partially effective. A further problem arises from small variations in receiver gain. Although each receiver is switched between the two channels, it is possible to have a small change in gain, $\delta(h)$, that affects only one channel. Such a variation will cause a fractional error in the measurement of P_s of the order of $(P_n/P_s)\delta$, which could be very large at great altitudes. A similar variation that affects both channels equally (the usual case) will produce only a small error of the order of δ. The detector presently employed is a linear one, a transistor version of the so-called "infinite impedance" detector, in which we have employed more than the usual amount of feedback. This detector has given the linear dynamic range and freedom from gain modulation required for the power profile measurements.

B. Faraday Rotation Profile. To obtain a Faraday profile, we transmit left and right hand circularly polarized pulses simultaneously and also receive both polarizations simultaneously, using synchronous detectors to obtain the real and imaginary components of the signal. After digitizing the signals, we multiply one component of one of them by both components of the other. It turns out that it is not necessary to obtain the other possible pair of cross products, since the information obtained is identical, statistically, to that given by the first pair. Nevertheless, it would be useful to have the second pair, since it would give us twice as many data samples in the same amount of time. Unfortunately, our present equipment can only compute two products. After averaging, the resulting two terms for each height are proportional to $P_s \sin\phi$ and $P_s \cos\phi$, where P_s is again the mean scattered signal power and ϕ is the phase shift between the two signals. It is not necessary to subtract out any noise term as in the power profile measurement, because the noise from the two receivers is uncorrelated and the product will have an average value of zero. The phase shift ϕ is made up of a constant term, due to differences in receivers, etc., and a term which varies with height, due to Faraday rotation. We have the well-known relation

$$\frac{d\phi}{dh} \sim N(h)\ B(h)\ \cos\Theta(h)$$

or (2)

$$N(h) = C(h)\ \frac{d\phi}{dh}$$

where B is the magnetic field strength and Θ is the angle between the beam direction and the magnetic field. The constant of proportionality C(h) can be calculated, in principle, from a knowledge of B and Θ. However, with Θ so near 90° (measurements have been made at $\Theta = 84.5^\circ$ and $\Theta = 87.1^\circ$), slight errors in the calculated values can lead to large errors in C(h). It has turned out to be more practical to compare Faraday profiles and ionograms to get a value of C at h_{max}, and then to compare Faraday and power profiles at times and altitudes where T_e/T_i is unity, to obtain the variation of C with h. Conveniently for us, C seems to be nearly independent of height, at least to altitudes of the order of 700 km or so. Apparently, increases in $\cos\Theta$ more or less cancel decreases in B over the height range 200-700 km. Our present data shows very good agreement throughout the day between the values of N_{max} obtained from ionograms and those obtained from Faraday profiles, even when h_{max} varies over a range of 200 kms.

The reduction of the data to obtain profiles is done on-line with a computer. From the values of $P_s \sin\phi$ and $P_s \cos\phi$, we calculate $d\phi/dh$ and multiply by the constant C to find the electron density. It may be noted that we can handle the data differently. The square root of the sum of the squares of the two terms gives us P_s, which can now be treated exactly as in the case of the power profile. However, during the day, when the total electron content of the ionosphere is high, the "Faraday power profile" is sometimes distorted because of Faraday dispersion effects due to the finite width (about 1^o) of the antenna beam. The variation of Faraday rotation across the beam causes destructive interference of complex correlation coefficient terms from different parts of the beam, and so the power apparently received from a given height is reduced by an amount dependent upon the total electron content below that height. During the night, this problem is not serious, and the two types of power profiles agree well with each other. They also agree well at night with the profile obtained by differentiating the Faraday rotation (the "Faraday angle profile") over the entire range of the latter. This implies that T_e/T_i is a constant (presumably unity) throughout the ionosphere at night, at the equator.

During the day, the power profiles are normalized by fitting them to the Faraday angle profile on the top side of the ionosphere. Except near sunrise, the profiles fit well above about 400 km. Measurements of the autocorrelation function confirm that T_e/T_i has indeed dropped to unity at this height. Thus we have considerable confidence in this method of fitting the curves on the top side. Below h_{max}, the power measurement gives a value smaller than the Faraday angle measurement, implying that T_e/T_i is greater than one. By comparing the two values, one can determine T_e/T_i. Occasional comparisons with autocorrelation function measurements have confirmed the values of T_e/T_i obtained. At times, usually at night, it is not possible to obtain N_{max} from ionograms because of interference from spread-F echoes or because of very low electron densities. In many cases, however, it is still possible to obtain electron densities over at least a limited height range from the Faraday rotation measurement, thus allowing the power profiles to be normalized. We have succeeded in measuring an N_{max} as low as 1.65×10^4/c.c. in this way, even though this density corresponds to a phase rotation rate of only about $.4^\circ$ in 20 km of path length (a 10 km height interval).

A point worth mentioning in connection with the Faraday measurement is that, for the Jicamarca location, the operating frequency of 50 Mc/s has fortuitously turned out to be fairly optimum. If the operating frequency were much higher, there would be so little rotation that it would be difficult to measure accurately. If the frequency were much lower, there would be so much rotation during the day that we would have serious convolution problems, since the Faraday angle would rotate through several radians in a height interval comparable to the pulse length. At Jicamarca, with the antenna beam directed 3° away from normal to the magnetic field, the maximum rate of phase rotation is almost one radian in a twenty kilometer height interval (a forty kilometer round trip path) for an electron density of 10^6/c.c.

C. Autocorrelation Function Measurement. The measurement of the autocorrelation function is practically the same as the measurement of the Faraday rotation. In this case, however, the transmitted right and left hand circularly polarized pulses are separated by a time delay Δt, and, in the multiplication of the received signals, a similar delay is inserted in the appropriate channel. The results obtained for each height are then $\overline{V_s(t)\, V_s^*\, (t + \Delta t)}\, \sin\phi$ and $\overline{V_s(t)\, V_s^*\, (t + \Delta t)}\, \cos\phi$ rather than $P_s \sin\phi$ and $P_s \cos\phi$ ($P_s = \overline{|V_s(t)|^2}$, the result for Δt equals zero). These measurements are made for several time delays (including zero) at each height, each value of Δt corresponding to one point on the autocorrelation function curve.

In principle, T_e, T_i, and the percentage composition of the positive ions in the ionosphere can be determined from the autocorrelation function. The theoretical curves, however, show that in many cases it would be very difficult to separate the effects of a change in composition from those due to changes in T_e/T_i[13]. This difficulty, of course, was one of the main reasons for developing the Faraday measurement in the first place, since a comparison of a Faraday angle profile and a power profile gives an independent determination of T_e/T_i. Fortunately, it appears from measurements so far obtained that, at least at the equator, changes in T_e/T_i and composition do not occur in the same range of height to any great extent. With the possible exception of the sunrise period, T_e/T_i is generally unity above about 400 km, whereas the ion composition does not begin to differ from pure O^+ until the altitude is somewhat greater.

3. Recent Results and Discussion

Profiles of the electron density have been obtained at Jicamarca since 1962[15]. However, due to construction and modification of equipment, these early measurements were made at rather irregular and widely-spaced intervals. Only recently has it been possible to adopt a reasonably regular schedule, and even now this is subject to interruptions. Since May, 1964, we have been observing for a continuous period of the order of forty-eight hours about once every four to eight weeks. The interval between runs will hopefully be shorter in the future.

In this paper, we shall concentrate our attention mainly on the more recent data, in particular on those of February, 1965, which are the most extensive and reliable obtained to date. All the data presented here correspond to quiet magnetic conditions.

A. Electron Density. Figures 1-6 show some typical contour plots of electron density as a function of altitude and local time. Except for regions in which the contours close, the plots were made by simply connecting the data points with straight lines. Thus the smoothness, or lack thereof, of the curves gives a rough idea of the uncertainty of the plotted values. These uncertainties in height naturally become large at altitudes above 1000 km where the scale height of the ionosphere becomes very great. The uncertainty in the height corresponding to given electron density may be large, even though the uncertainty in electron density for a given height is small. Generally the profiles from which these contour plots were made extend well beyond the limit of the contour plots, usually to at least 2000 km.

The times and regions in which spread-F interfered with the measurements are roughly indicated by the shaded areas. Where it was possible to estimate the height limits of the spread-F, these limits are indicated by a smooth boundary of the shaded area. A jagged edge, on the other hand, indicates that the boundary could not be determined. The upper boundary could frequently be estimated from examining power profiles, even when these profiles could not be normalized to obtain electron densities.

These contour plots illustrate with particular clarity the very rapid build-up of the ionosphere after sunrise, the frequently fairly stable conditions in the middle of the day and early evening, and the often almost complete disappearance of the F region just before dawn, at which time N_{max} sometimes falls to values of the order of 10^4/c.c.

In the September and October data shown in Figures 1-3, the ionosphere is fairly well behaved; there are no really violent vertical motions apparent, with the possible exception of the fairly rapid rise of h_{max} between 0900 and 1000 on 16 October. The contours for these days are quite smooth and in most cases there is clear evidence of a lag of several hours between the build-up of the F region in the neighborhood of 400-500 km and the build-up near 1000 km. Earlier measurements in May and July, 1964, showed very similar behavior.

In the November data shown in Figure 4, we can see evidence of substantial vertical drift motions, in particular the rapid rise of h_{max} during the period 2100-2300 on 18 September. Note that the electron density at and below h_{max} is decaying fairly rapidly in this interval, but at altitudes above 500 km, where the density had been diminishing previous to this time, the density remains constant or increases. This increase tends to be greater and somewhat more delayed at the higher heights.

The behavior of the top side of the ionosphere often tends to be more regular than that of N_{max}. On both days in November, the maximum density at 500 km occurred in the vicinity of 1100-1200 hours, with the maximum at 1000 km coming two or three hours later. N_{max} reaches its highest value even later than this, however, at a time when both the top side and the bottom side of the ionosphere are decaying. An important implication of this behavior is that substantial transport along the magnetic field lines is occurring on the top side.

The effects of vertical motion are dramatically apparent in the data of 1-3 February, 1965, shown in Figures 5 and 6. In Figure 5 we have plotted the contours for the whole period in order to show the marked similarity of the three days. Almost every important feature of the curves is repeated to a remarkable degree. Note the considerable effect on the contours of the sharp rises in h_{max} which end at 1930 and 2300 hours on both 1 and 2 February. The effect is more pronounced on 2 February and causes a sharp reversal in the decay of the top side. As in the other examples given earlier, the effect of this rise appears to propagate upwards, requiring about two hours to reach the highest heights shown.

Another rather spectacular vertical motion, in this case downwards, can be seen from the contours to take place between 0000 and 0200 on 3 February. In this period, the ionosphere plunges down nearly 200 km without any appreciable change in N_{max} and very little change in shape other than a slight compression. This rapid drop can be seen more clearly from the actual profiles, shown in Figure 7. The profile of 0323 is included to illustrate the rapid predawn decay of the F region, once it reaches a low altitude. Each curve corresponds to a time period of 10-15 minutes beginning with the time listed.

In February, we were quite successful in obtaining good measurements of electron density to altitudes of several thousand kilometers throughout the period of observation. Six typical profiles spaced throughout one 24-hour period are shown in Figure 8. In Figure 9 are shown three profiles taken at nearly identical times on three successive days. The results can be seen to be remarkably consistent. Each profile in these two figures was constructed by fitting together a Faraday profile and two or three power profiles. The time given in the figures corresponding to each curve is the time at which the integration for the Faraday profile was started. The total integration time for the series of measurements required for each profile was generally between 40 and 60 minutes.

The accuracy of the daytime profiles is estimated to vary between roughly $\pm$ 2% near h_{max} and perhaps $\pm$ 20% at altitudes above 4000 km. As mentioned before, the detailed agreement between values of N_{max} obtained from Faraday profiles and ionograms is very good, when the electron density is sufficiently high (greater than, say, 10^5/c.c.). At high altitudes, the accuracy naturally decreases because of the decreasing signal to noise ratio. Additional small errors are introduced at each point where two curves are fitted together to form the final profile. The largest sources of error at the greatest heights, however, are usually minute variations in the receiving system characteristics and/or noise leakage from the transmitter. These variations are only troublesome if they are synchronized with the transmitted pulses, which is most likely to occur when long pulse lengths, such as 5 ms, are used. To a very large extent, these effects have been eliminated, but with the roughly 30 db of integration used at the extreme altitudes, even very small residual effects become important. These small residuals are steadily being reduced, which should allow us to reach considerably higher heights in the future.

In the early morning, before sunrise, when the F region has practically disappeared, the main problem has generally been in normalizing the profiles. The relative accuracy of the power profiles is still quite good, but the Faraday angle profile becomes very noisy. Frequently, ionosonde records are not available in this period, either because of mild spread-F or because of the extremely low values of foF2, and so the Faraday profiles must be used. The profile taken at 0428 on 3 February in Figure 8 is a good example. Here N_{max} was measured by Faraday rotation to be only 1.65×10^4/c.c. corresponding to an foF2 only slightly above 1 Mc/s and a phase rotation of only about four degrees in a 100 km height interval. In this case, the whole profile is probably accurate to only ± 20%, although the relative accuracy of the shape of the profile is much better.

It is interesting to note that, at this time, the minimum density for the whole profile occurs at an altitude of about 500 km. On some occasions, we have observed that even the small vestige of an F region still apparent on this profile disappears entirely just before sunrise; the density is nearly constant in and above the F region and there is no discernible N_{max}. Unfortunately, these profiles could not be normalized.

In Figure 10, we have shown the variation of electron density at selected heights up to 4000 kilometers throughout the period of the February observations. As we have also seen from other figures, the density changes very slowly with height at 3000 km and above. It maximizes at about 1700 hours and reaches a minimum somewhat after midnight. The change in density from maximum to minimum is only about a factor of two.

Several aspects of the behavior of the ionosphere mentioned in connection with earlier figures are even more clearly apparent in Figure 10. We note, for instance, the great similarity of the three days, the often marked difference in behavior between N_{max} and values of N at a constant height, the time lag between peaks at successive heights, and the occasional sharp increases and decreases in N_{500} and N_{700} associated with rising or falling values of h_{max}. It is clear that transport effects are a very important factor in the equatorial ionosphere.

In Figure 11, we have compared the high altitude results of February with various whistler observations reviewed by Carpenter and Smith.[16] The range of densities observed at Jicamarca at 5000 km is seen to agree quite well with the whistler observations, although perhaps this agreement is somewhat fortuitous since most of the whistler observations were made in 1962 or earlier.

B. Measurements of T_e/T_i. Figure 12 shows the variation of T_e/T_i during the February observations. These values of T_e/T_i were all determined by comparing Faraday rotation and power profiles. No measurements of the autocorrelation function were made during this period because of difficulties with the equipment. The accuracy of the values of T_e/T_i is estimated to be about $\pm$ .2. The consistency of the results from day to day is not as good as that of the electron density measurements. This may be a real effect, but more probably it reflects uncertainties in the measurements. Much of the uncertainty arises from small errors in fitting Faraday and power profiles together on the top side of the ionosphere. Slight errors in the profiles or slight changes in the ionosphere during the period between two measurements can lead to small errors in normalization. These errors generally do not alter the values of electron densities significantly but can cause appreciable errors in the determination of T_e/T_i.

These results are reasonably typical of results obtained in earlier months, although in this case, non-equilibrium extends to somewhat greater heights than observed previously. Nevertheless, it appears clear that at the equator, non-equilibrium does not extend to heights nearly as great as those observed at temperate latitudes.[17] There is evidence that, during sunrise, the values of T_e/T_i are substantially higher than those of Figure 12, and that non-equilibrium extends to greater heights. Measurements are difficult to make during this time, however, because of rapidly changing conditions and low electron densities, and so results obtained to date must be considered as only preliminary.

A typical early morning result for July is shown in Figure 13. The solid and dotted curves are the "Faraday angle" and "Faraday power" profiles, respectively. The angle measurement gave quite noisy results above 400 km. The dotted curve was normalized by making use of a measurement of the autocorrelation function made immediately before the Faraday measurement. The former determined T_e/T_i at the heights indicated and thus gave a separation between the two profiles. The power profile was then normalized to obtain the best fit.

C. Composition Measurements. Figures 14 and 15 show two of the composition determinations so far obtained. As yet, we have not begun to make these measurements on a regular basis, but the curves shown are typical of the results obtained to date. During the day, we do not find any significant number of helium ions in the ionosphere. We could have detected any concentration greater than 10% of the total. During the night, on the other hand, there appears to be a significant amount of helium, as indicated on Figure 15. The uncertainties in the night-time measurements are still quite large, but there seems to be little doubt that helium was observed. In the future, we plan to make much more extensive use of measurements of the autocorrelation function to obtain compositions and temperatures. Unitl now, these measurements have been greatly hampered by the small capacity of our digital integrator. This has now been greatly expanded.

Acknowledgements

Many people contributed significantly to the results reported here. The efforts of J. L. Green and R. A. Abney insured the successful operation of the equipment during the observations. D. S. Sterling wrote some of the computer programs required in the data reduction. J. P. McClure and R. Cohen assisted in the analysis of the data, and all of the above aided in taking the observations. The author is also indebted to K. L. Bowles for several helpful suggestions concerning the final manuscript.

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Figure Captions

Figures 1-5. Contours of electron density.

Figure 6. Part of Figure 5 with an expanded time scale.

Figure 7. A series of electron density profiles illustrating a rapid decrease in the height of the F region. The times listed are the local times at which the profile was begun. Each measurement required 10-15 minutes.

Figure 8. A series of electron density profiles taken throughout a 24-hour period. Each was taken over a period of 40-60 minutes, beginning with the local time indicated.

Figure 9. Three profiles of electron density taken at nearly the same time on three successive days.

Figure 10. The variation of the electron density at a constant height. The height, in kilometers, corresponding to each curve is indicated. The behavior of N_{max} and h_{max} are shown for comparison.

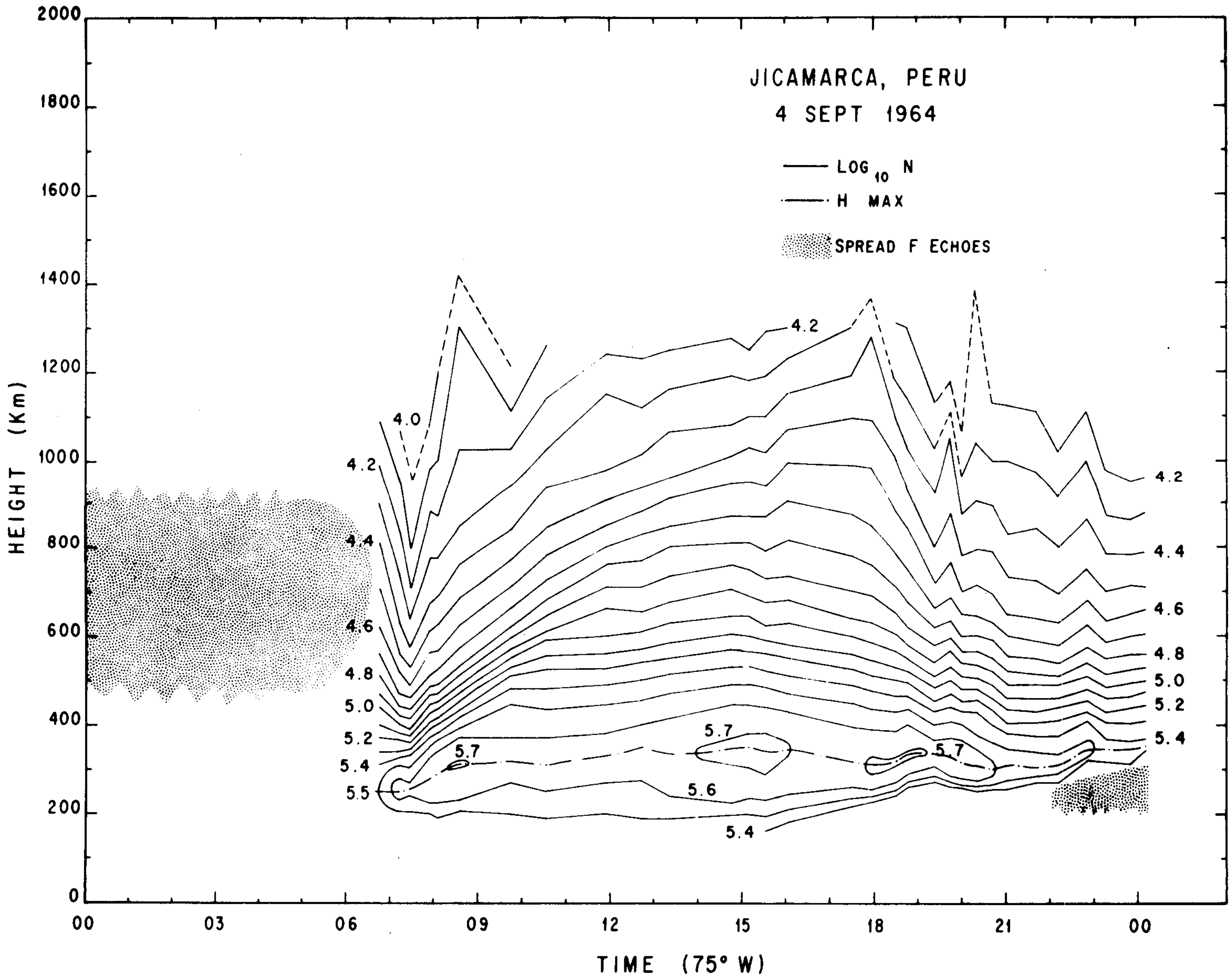
Figure 11 Comparison of electron densities obtained at Jicamarca with those obtained from whistler measurements. This figure is adapted from Figure 8 of Carpenter and Smith[16].

Figure 12. The dependence of T_e/T_i on altitude and time of day.

Figure 13. An early morning measurement of T_e/T_i.

Figure 14. Ionic composition and temperature of the ionosphere during the day.

Figure 15. Ionic composition and temperature of the ionosphere during the night.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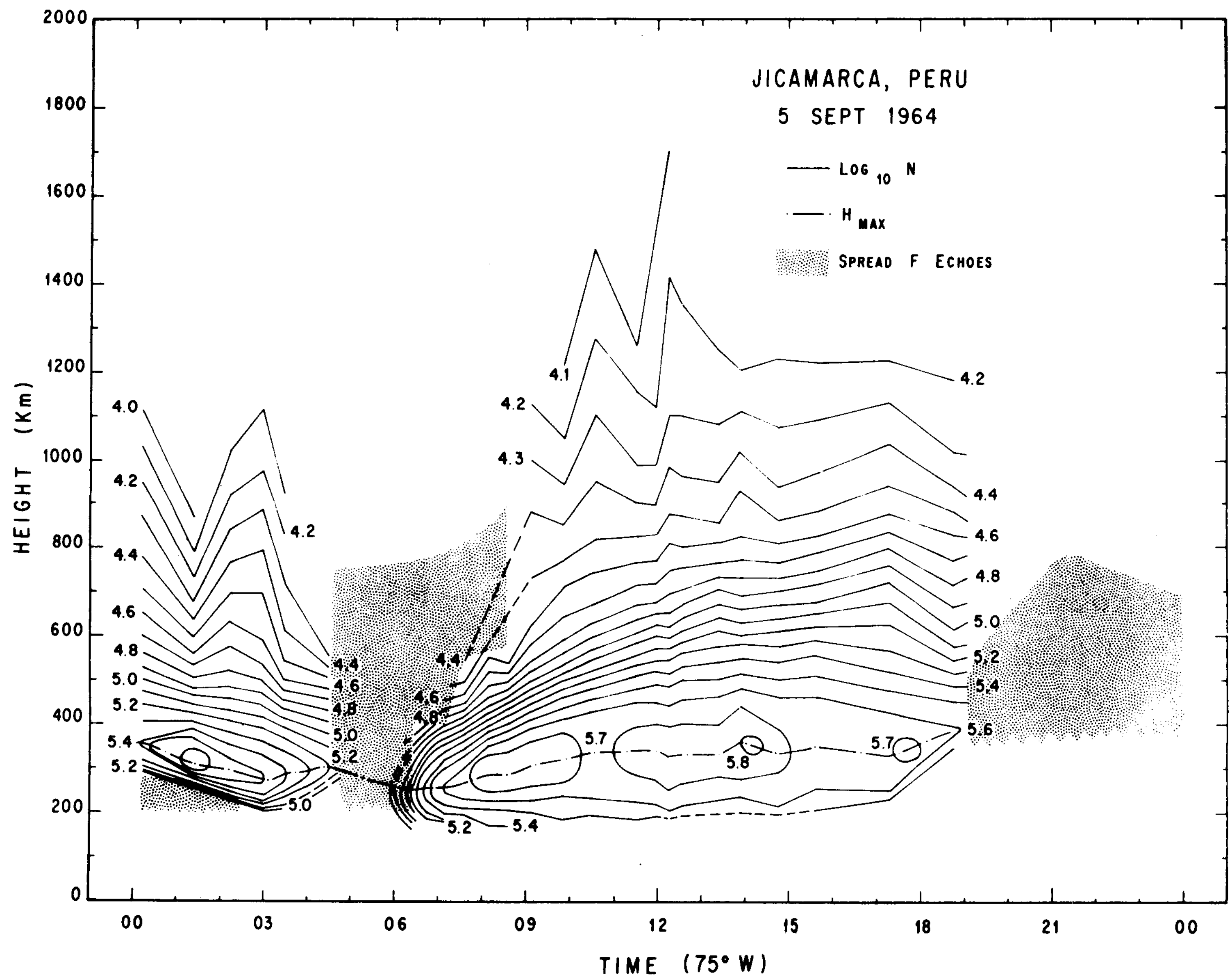

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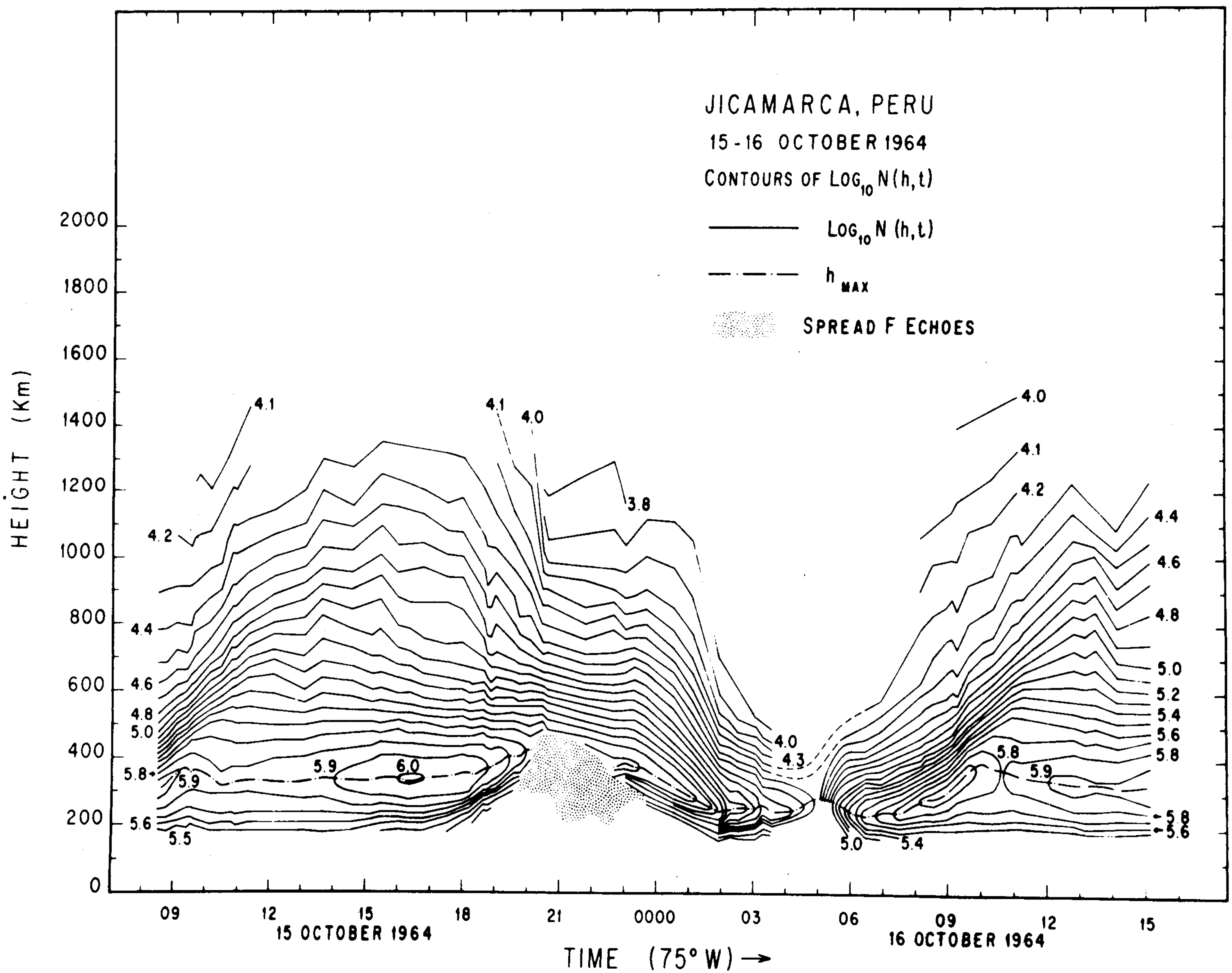
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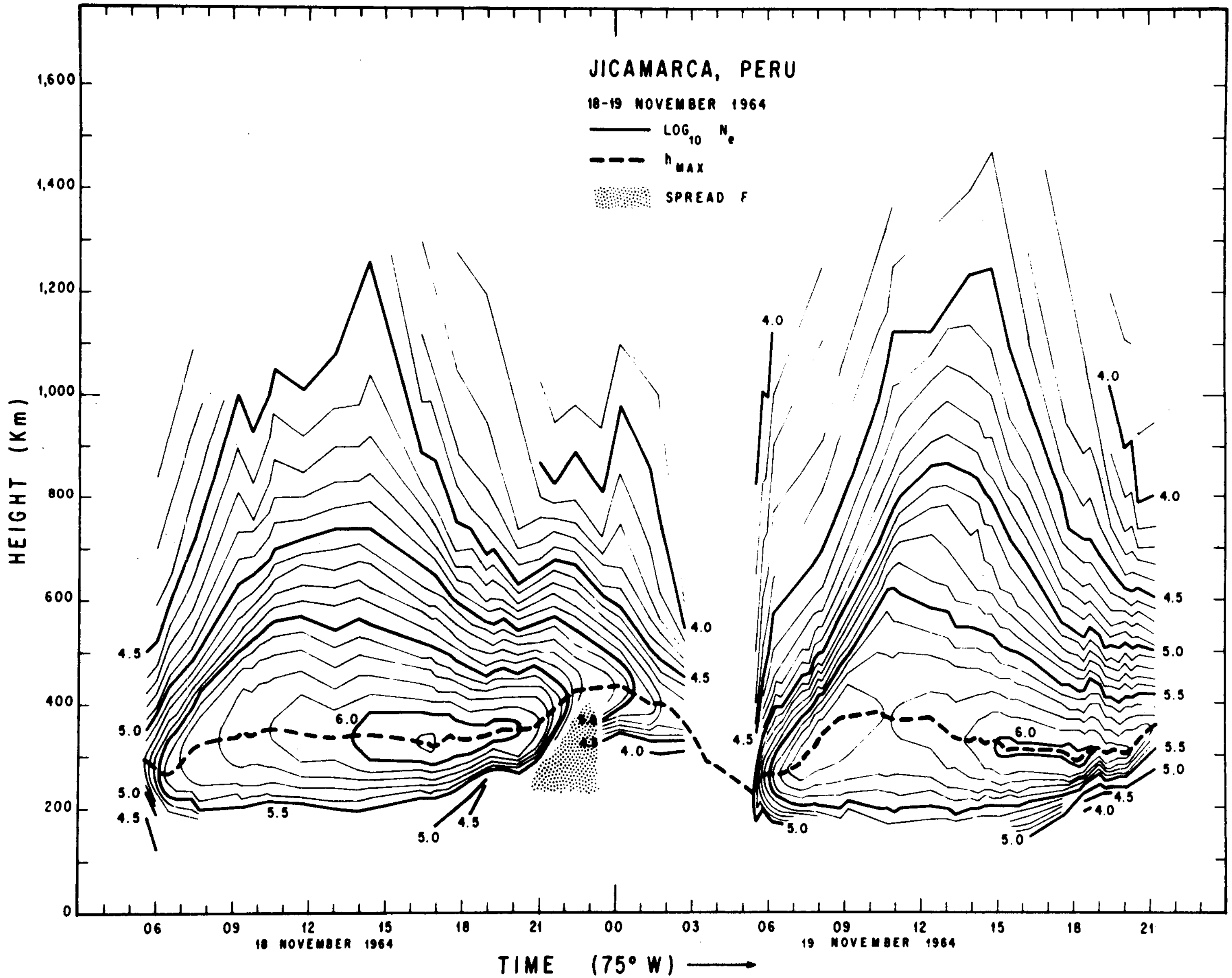
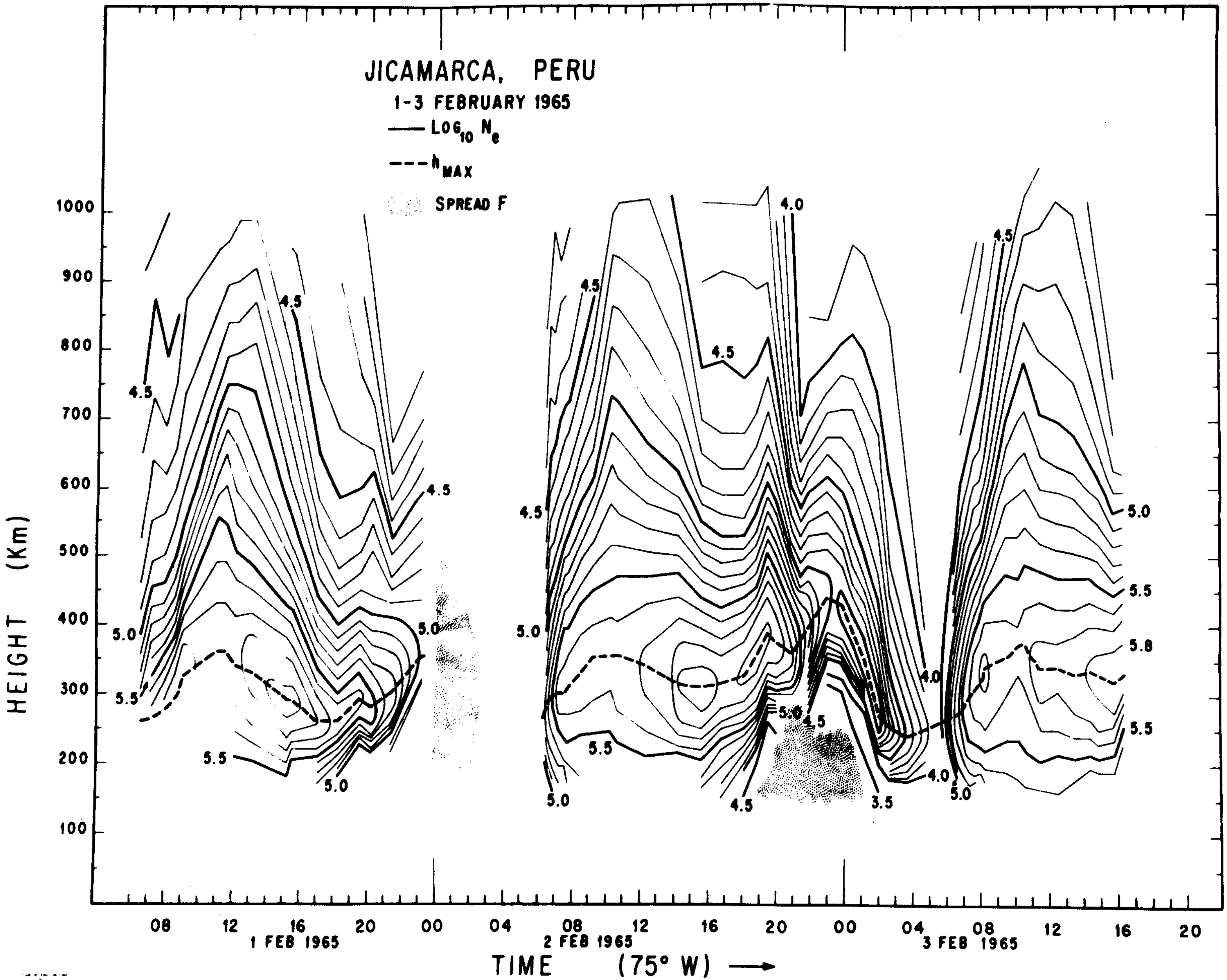
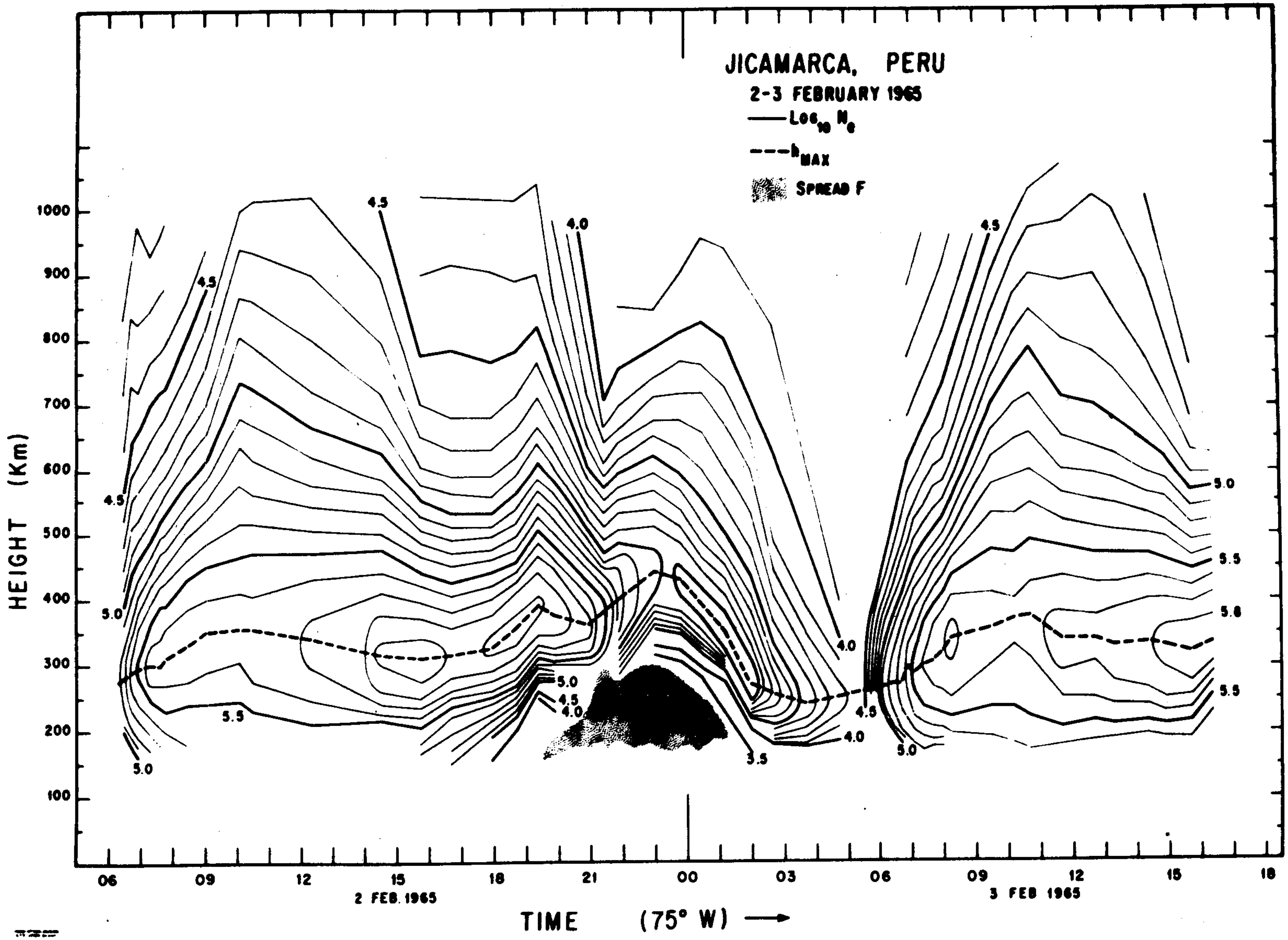
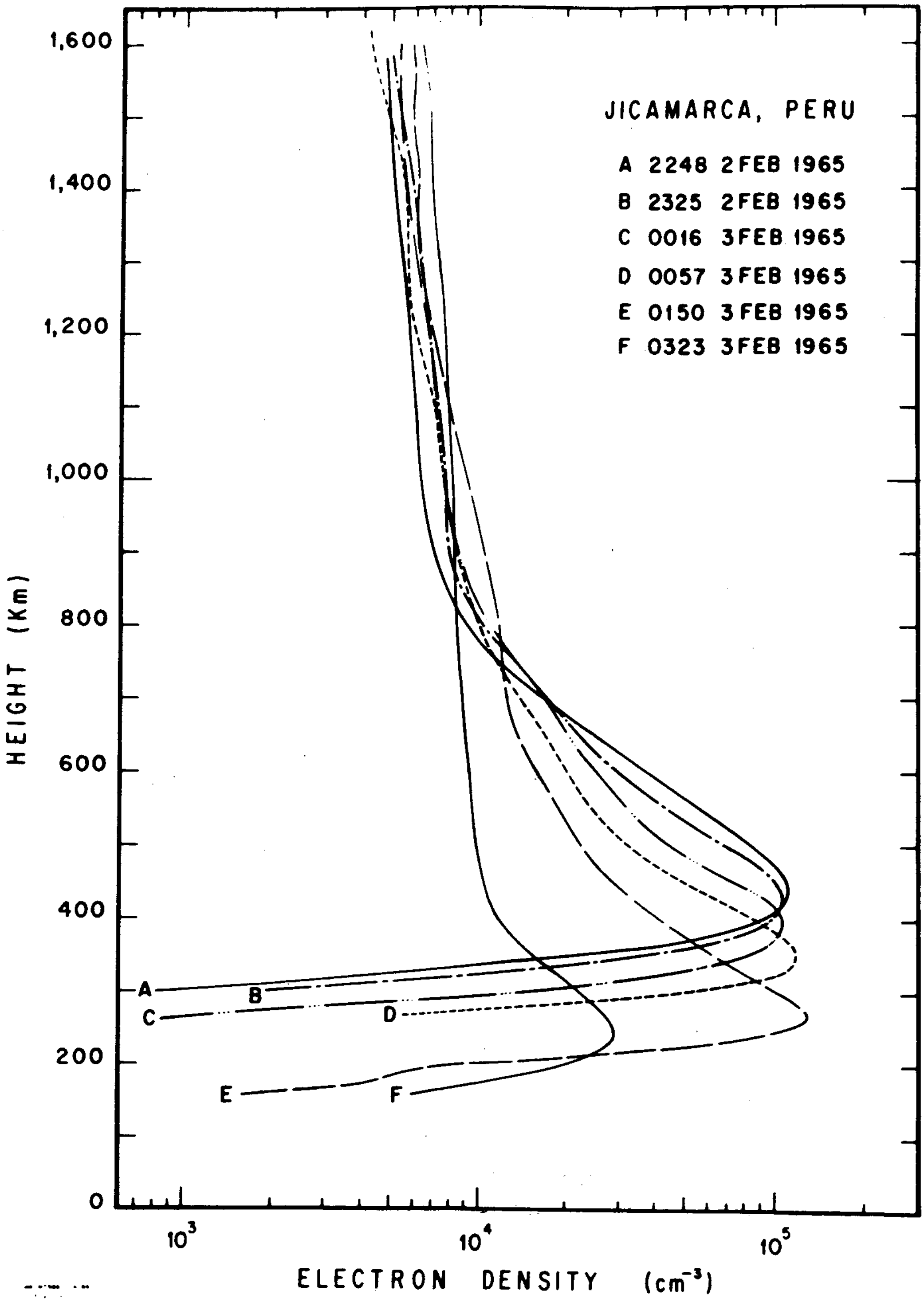
5.6
5.5
5.9
6.0
4.1
4.0
3.8
4.0
4.3
5.0
5.4
5.8
5.9
4.0
4.1
4.2
4.4
4.6
4.8
5.0
5.2
5.4
5.6
5.8
5.8
5.6

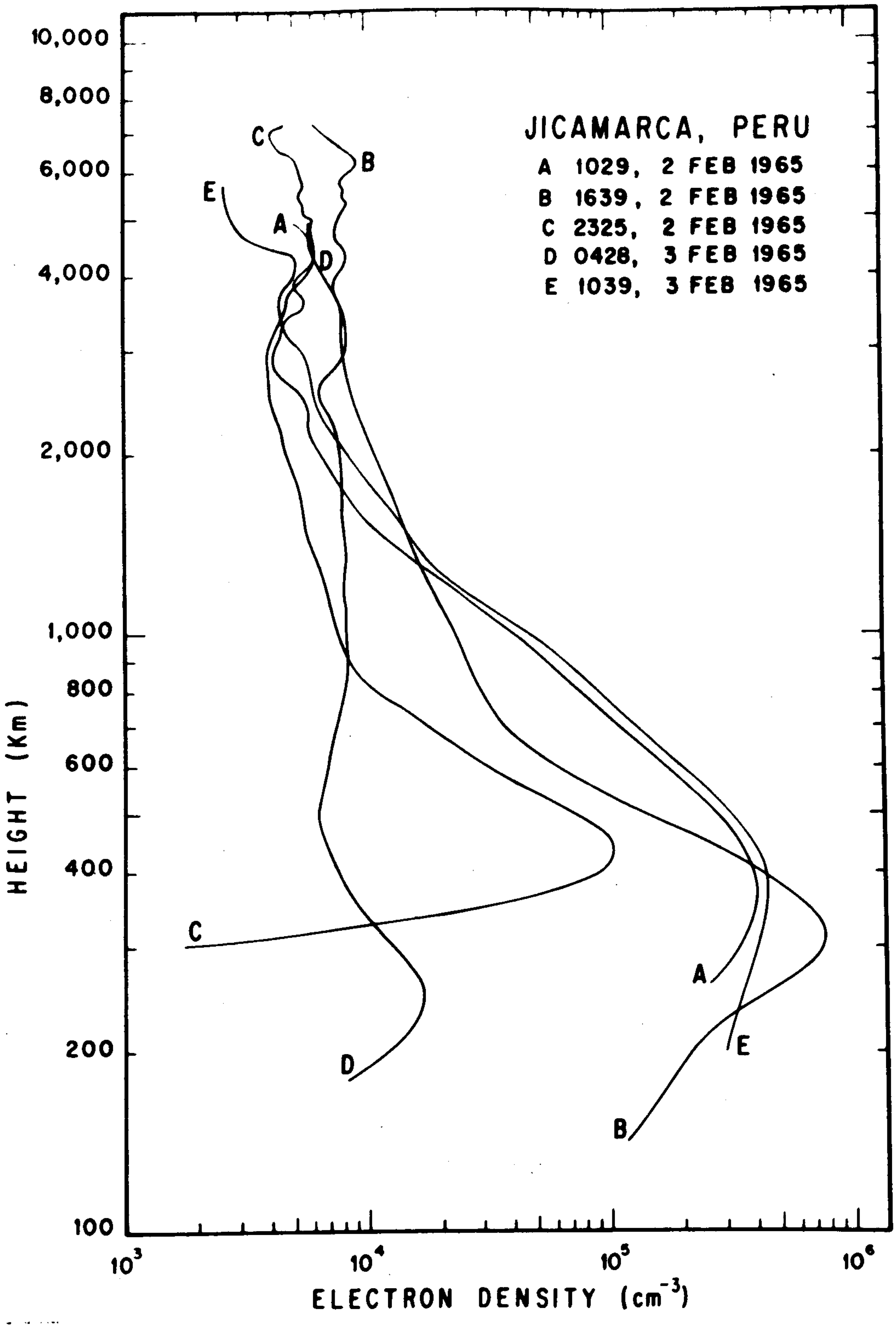

JICAMARCA, PERU
18-19 NOVEMBER 1964
LOG10 Ne
hMAX
SPREAD F
HEIGHT (Km)
1,600
1,400
1,200
1,000
800
600
400
200
0
06
09
12
15
18
21
00
03
06
09
12
15
18
21
18 NOVEMBER 1964
19 NOVEMBER 1964
TIME (75° W)
4.0
4.5
5.0
5.5
6.0

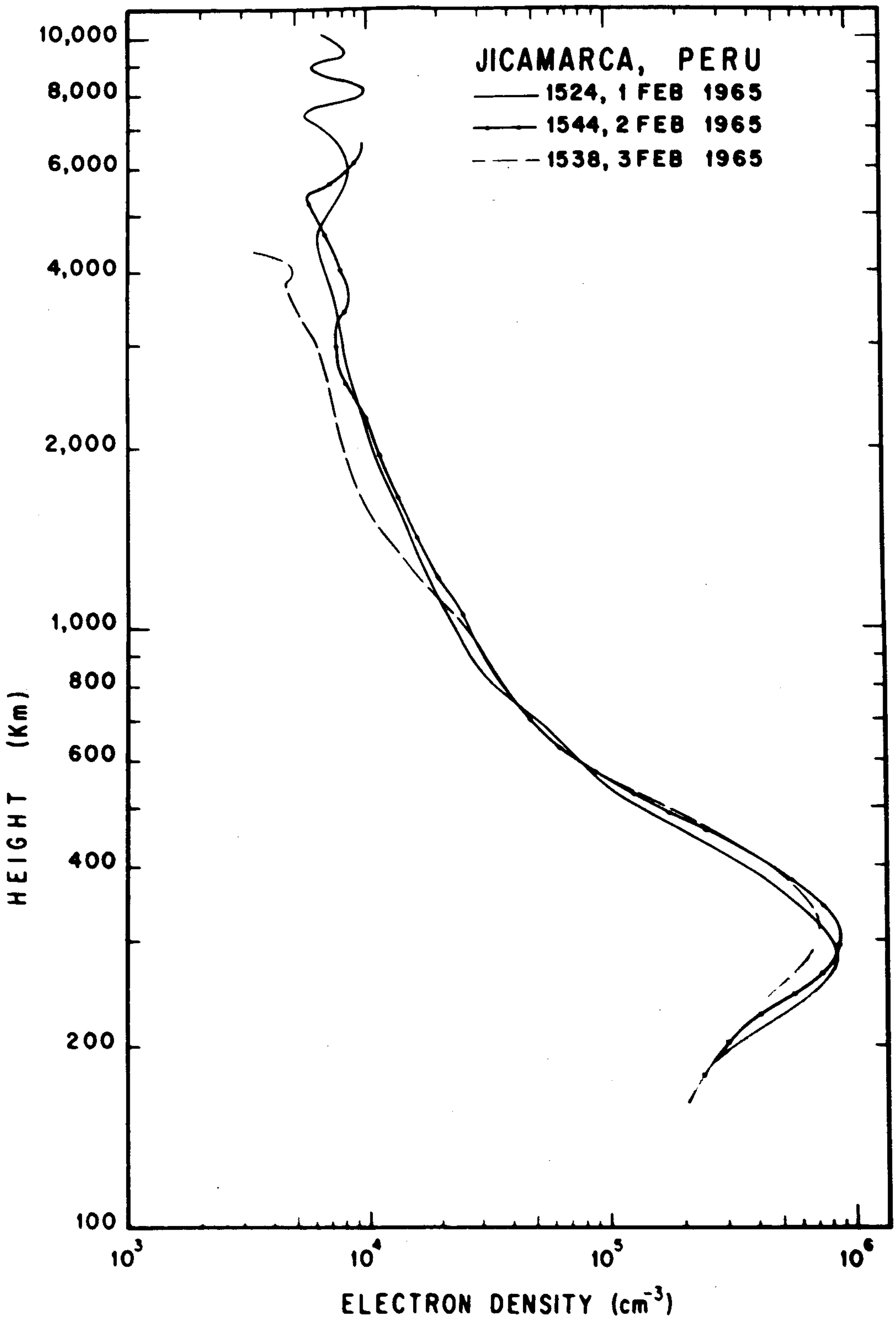


JICAMARCA, PERU
1-3 FEBRUARY 1965
LOG10 Ne
hMAX
SPREAD F
HEIGHT (Km)
TIME (75° W)
1 FEB 1965
2 FEB 1965
3 FEB 1965

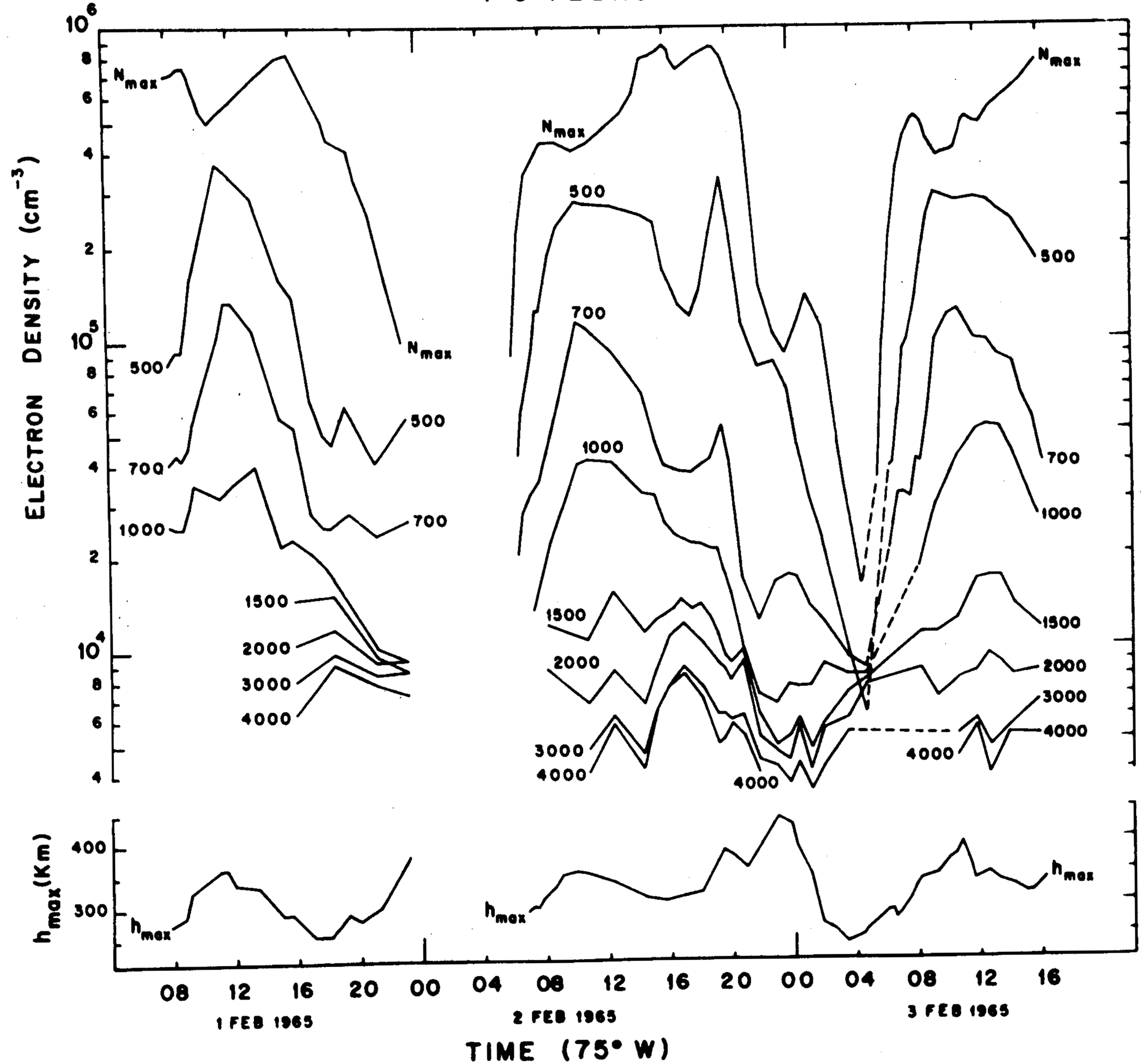

JICAMARCA, PERU
2-3 FEBRUARY 1965
Log$_{10}$ N$_e$
h$_{MAX}$
SPREAD F
HEIGHT (Km)
1000
900
800
700
600
500
400
300
200
100
4.5
5.0
5.5
4.0
3.5
5.8
06
09
12
15
18
21
00
03
06
09
12
15
18
2 FEB. 1965
3 FEB 1965
TIME (75° W)

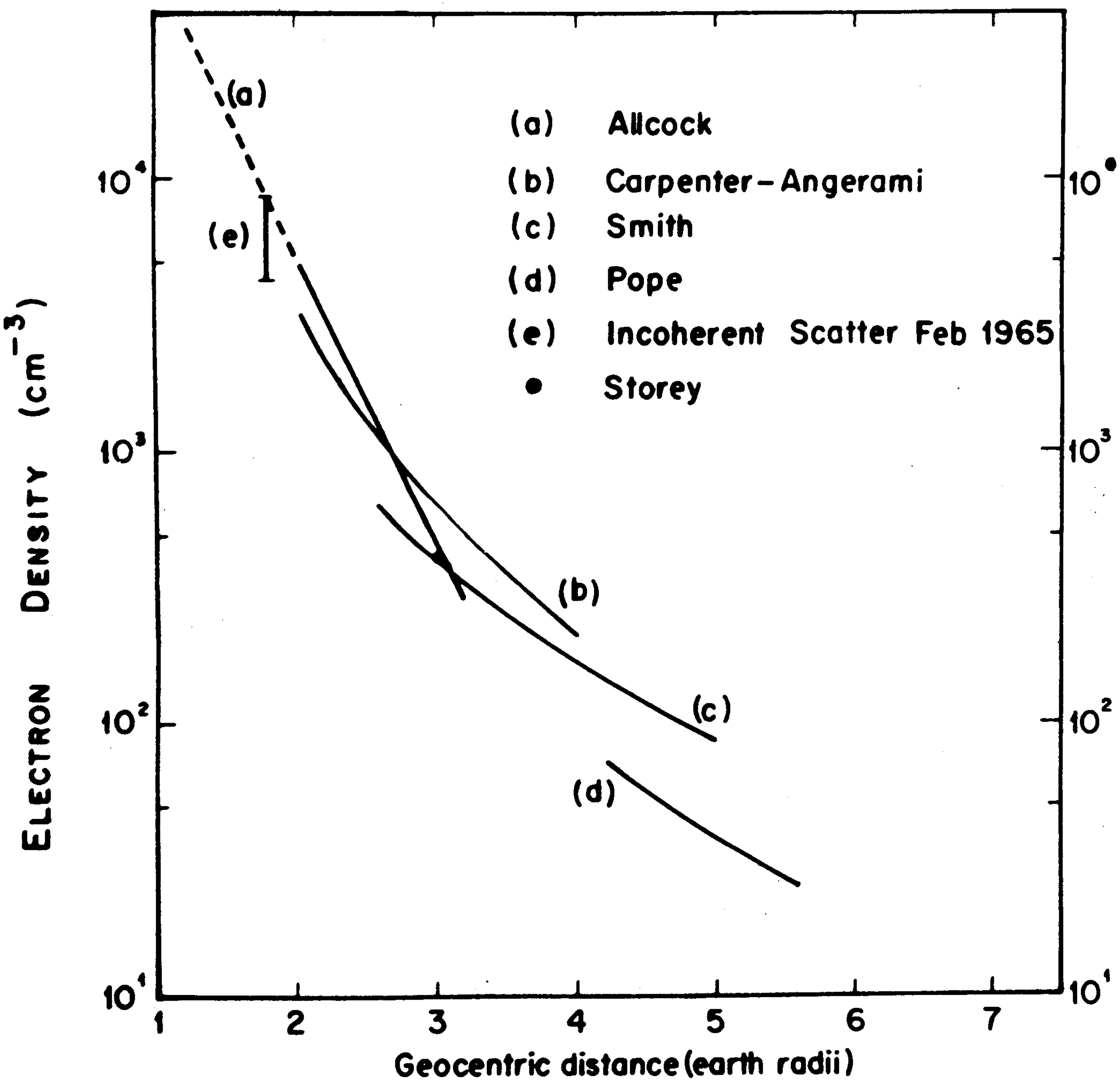

JICAMARCA, PERU
A 2248 2 FEB 1965
B 2325 2 FEB 1965
C 0016 3 FEB 1965
D 0057 3 FEB 1965
E 0150 3 FEB 1965
F 0323 3 FEB 1965
HEIGHT (Km)
1,600
1,400
1,200
1,000
800
600
400
200
0
A
B
C
D
E
F
10^3
10^4
10^5
ELECTRON DENSITY (cm^-3)


JICAMARCA, PERU
A 1029, 2 FEB 1965
B 1639, 2 FEB 1965
C 2325, 2 FEB 1965
D 0428, 3 FEB 1965
E 1039, 3 FEB 1965
HEIGHT (Km)
10,000
8,000
6,000
4,000
2,000
1,000
800
600
400
200
100
ELECTRON DENSITY (cm^{-3})
10^3
10^4
10^5
10^6
A
B
C
D
E

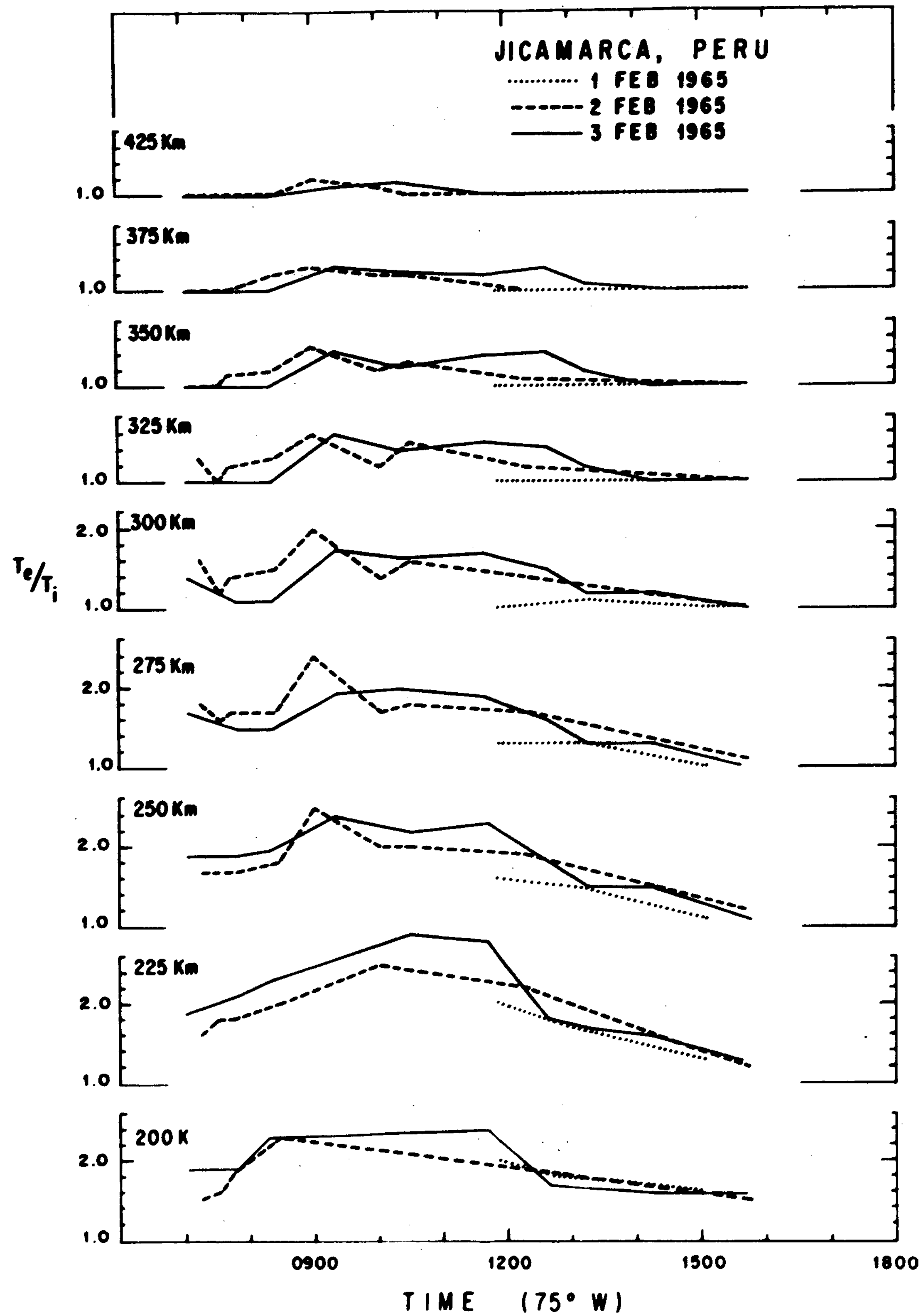

JICAMARCA, PERU
1524, 1 FEB 1965
1544, 2 FEB 1965
1538, 3 FEB 1965
10,000
8,000
6,000
4,000
2,000
1,000
800
600
400
200
100
HEIGHT (Km)
10^3
10^4
10^5
10^6
ELECTRON DENSITY (cm^{-3})

JICAMARCA, PERU
1-3 FEBRUARY 1965

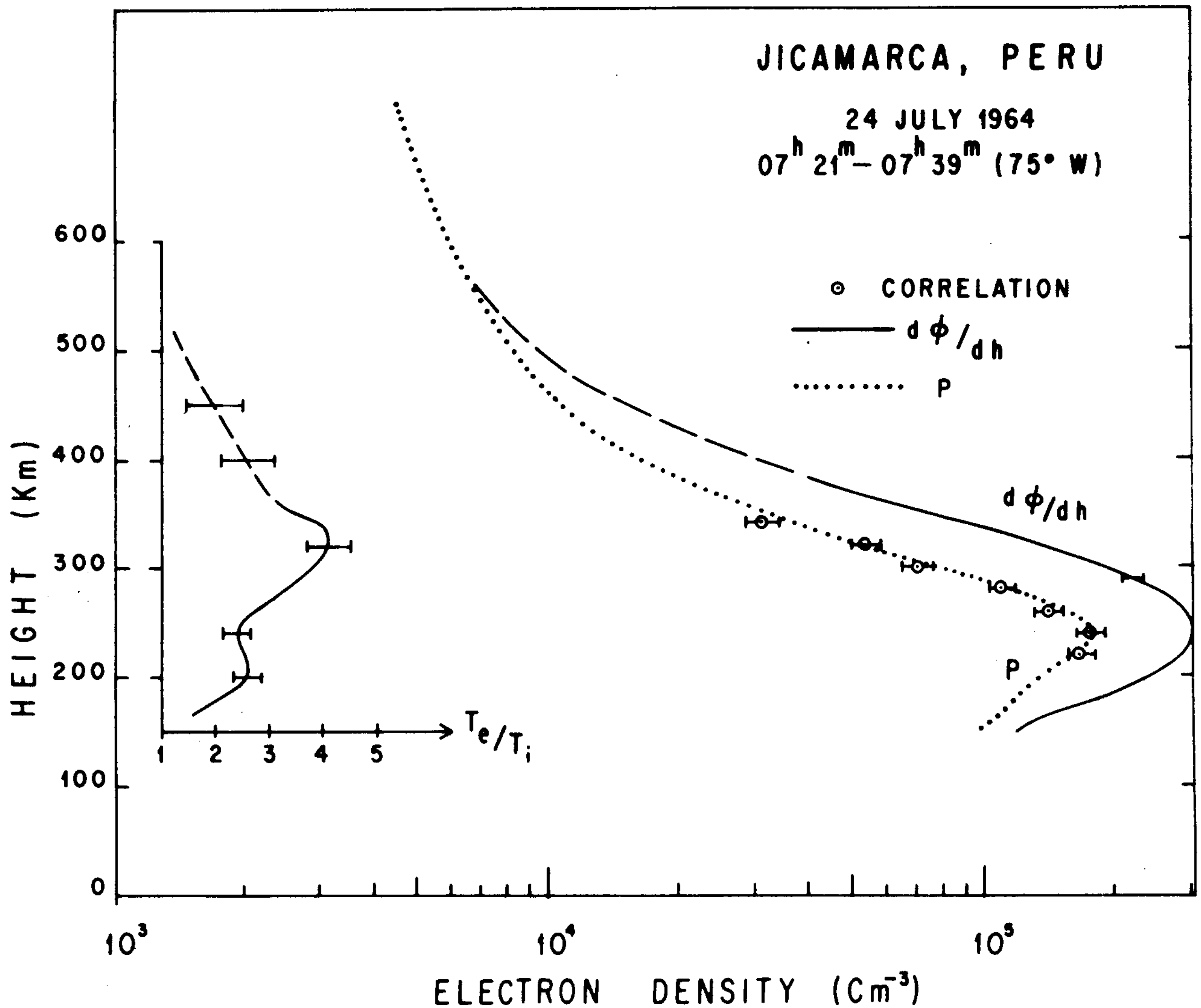




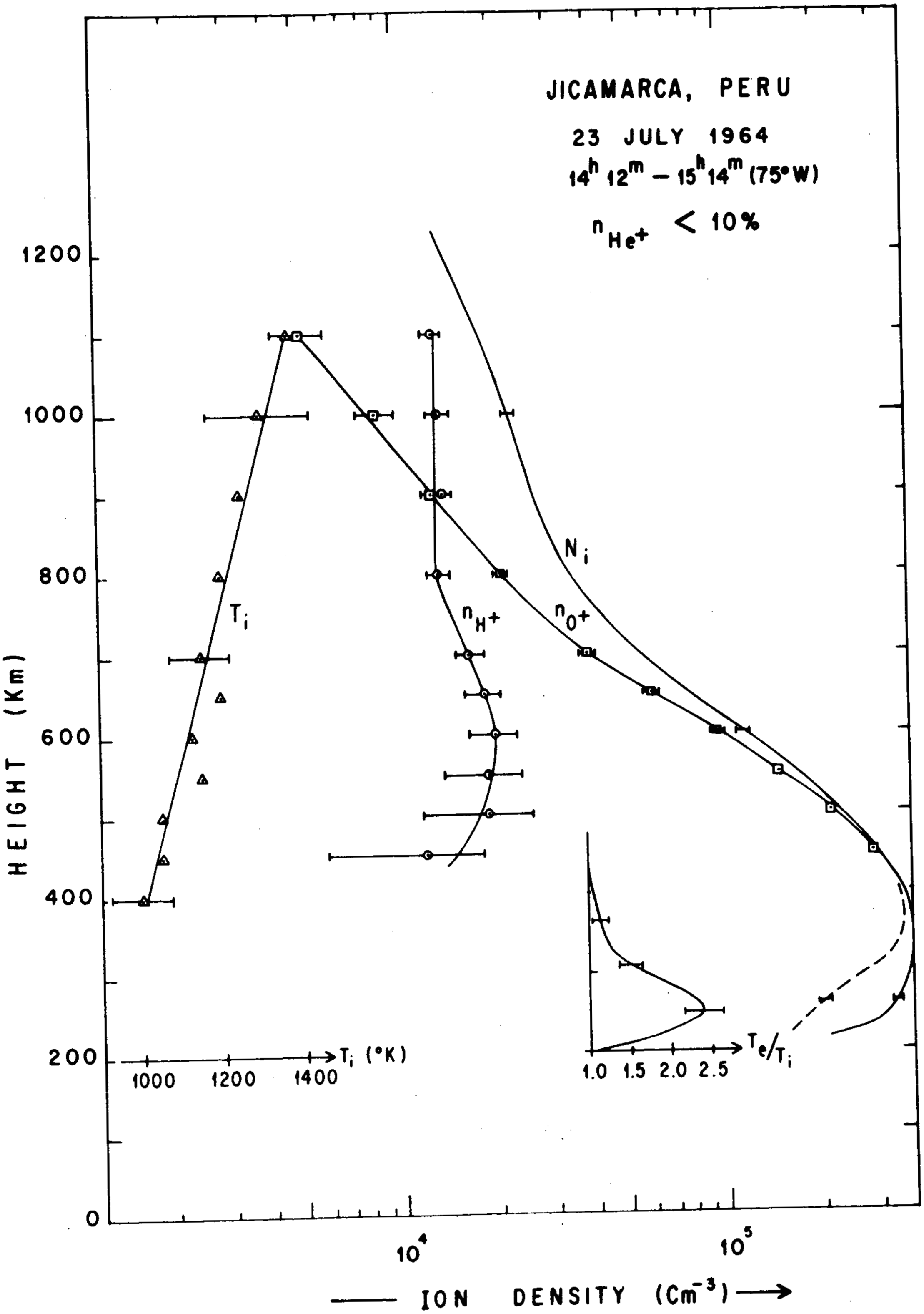
(a) Allcock
(b) Carpenter - Angerami
(c) Smith
(d) Pope
(e) Incoherent Scatter Feb 1965
Storey
(a)
(b)
(c)
(d)
(e)
ELECTRON DENSITY (cm⁻³)
10⁴
10³
10²
10¹
1
2
3
4
5
6
7
Geocentric distance (earth radii)



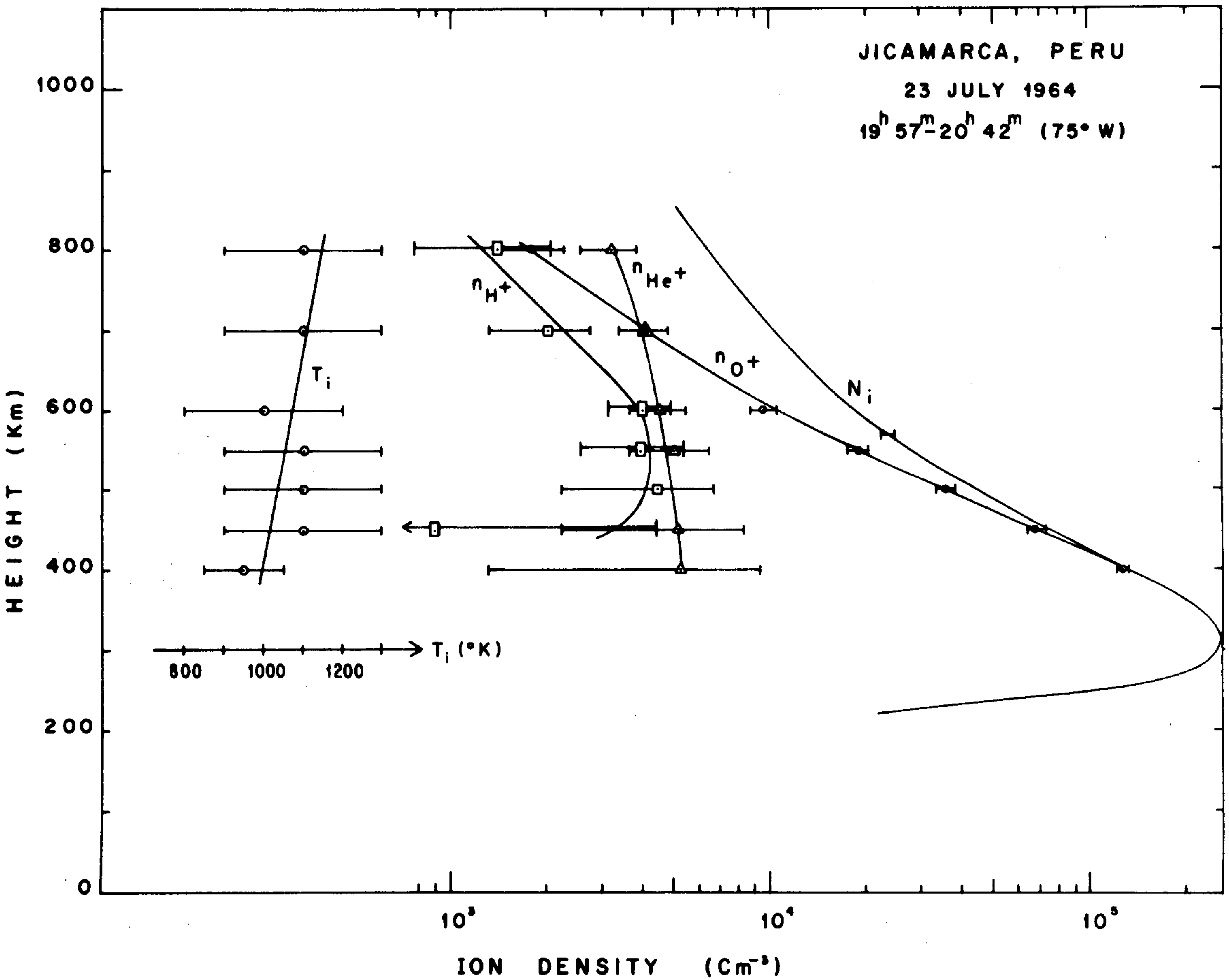
JICAMARCA, PERU
1 FEB 1965
2 FEB 1965
3 FEB 1965
425 Km
375 Km
350 Km
325 Km
300 Km
275 Km
250 Km
225 Km
200 K
1.0
2.0
T_e/T_i
0900
1200
1500
1800
TIME (75° W)



JICAMARCA, PERU
24 JULY 1964
07h 21m – 07h 39m (75° W)
CORRELATION
dφ/dh
P
dφ/dh
P
HEIGHT (Km)
0
100
200
300
400
500
600
1
2
3
4
5
Te/Ti
10³
10⁴
10⁵
ELECTRON DENSITY (Cm⁻³)



JICAMARCA, PERU
23 JULY 1964
14h 12m — 15h 14m (75°W)
n He+ < 10%
HEIGHT (Km)
1200
1000
800
600
400
200
0
Ti
nH+
nO+
Ni
Ti (°K)
1000
1200
1400
Te/Ti
1.0
1.5
2.0
2.5
10^4
10^5
ION DENSITY (Cm^-3)



JICAMARCA, PERU
23 JULY 1964
19h 57m - 20h 42m (75° W)
HEIGHT (Km)
1000
800
600
400
200
0
ION DENSITY (Cm⁻³)
10³
10⁴
10⁵
Tᵢ
n H+
n He+
n O+
Nᵢ
Tᵢ (°K)
800
1000
1200

15